Phenomenological BRDF Modeling For Engineering Applications

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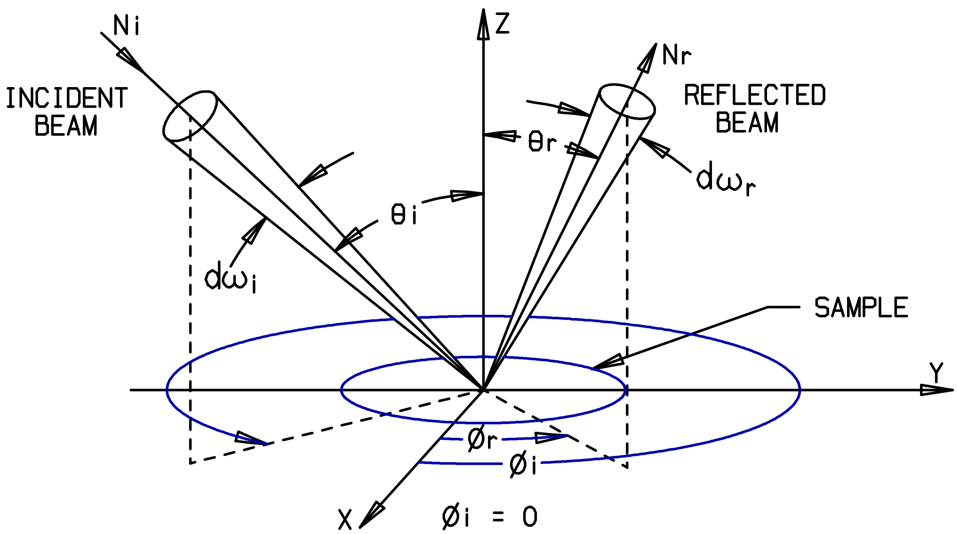
Outline

- BRDF Definition
- Optical Measurements
- Optical Properties of Materials
- Phenomenological BRDF Modeling
- Parameterized BRDF Models
- Conclusions

Bidirectional Reflectance Distribution Function (BRDF)



BRDF: $\rho'(\theta_i, \theta_r, \phi)$

$$\frac{\delta N_r(\theta_r, \phi)}{N_i(\theta_i)} = \rho'(\theta_i, \theta_r, \varphi)\cos\theta_i \delta\Omega_i$$

DHR: $\rho_D(\theta_i)$

$$\frac{N_r}{N_i(\theta_i)} = \iint \rho'(\theta_i, \theta_r, \varphi)\cos\theta_r \sin\theta_r d\theta_r$$

$$= \rho_D(\theta_i)$$

$\hat{n}$ = **Outward Surface Normal Unit Vector**

θ_i = **Incident Zenith Angle**

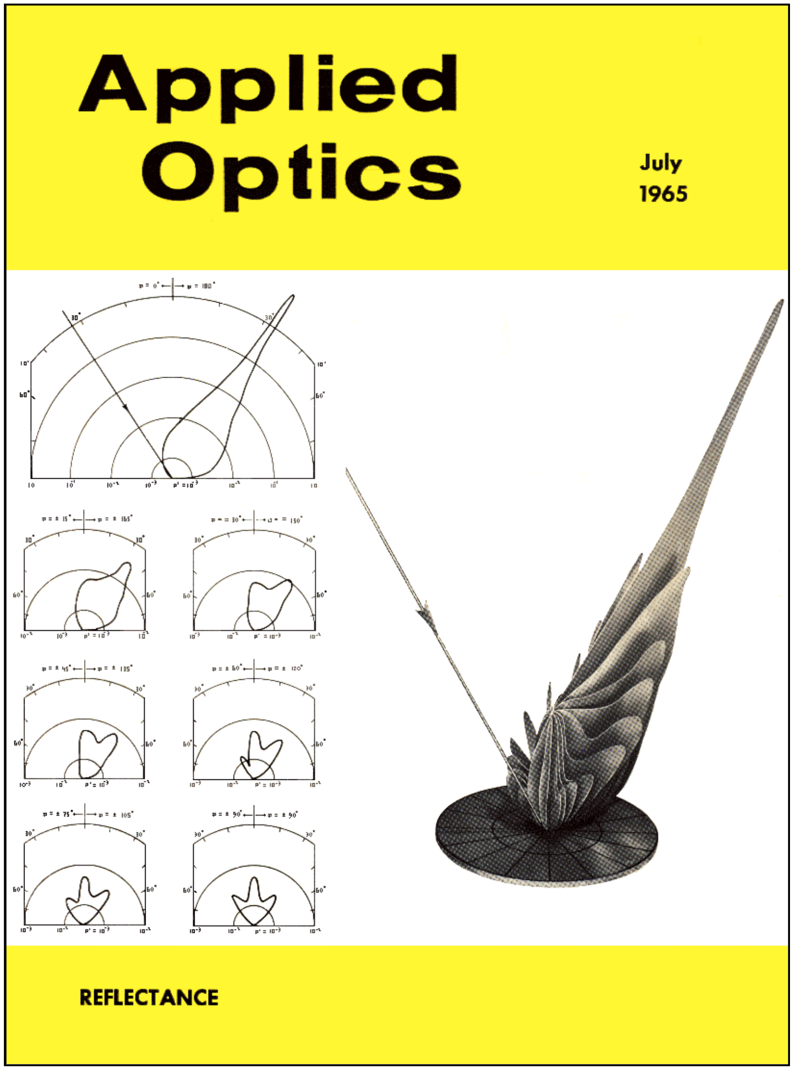
θ_r = **Reflected Zenith Angle**

ϕ = **Reflected Azimuth Angle**

(These apply to isotropic surfaces; also, $\phi \equiv \phi_r - \phi_i$ **here.)**

$\pi\rho' = \rho_D$ **For Lambertian Diffuse Surface**

Pictorial Representation of BRDF



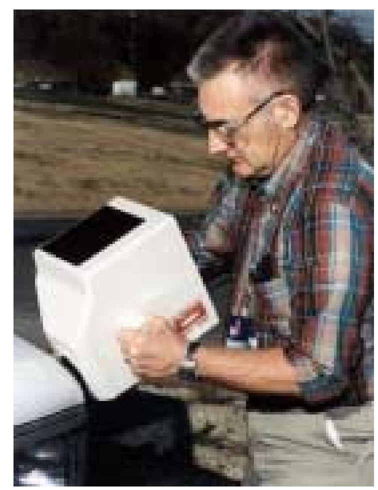
F. Nicodemus, "Directional Reflectance and Emissivity of an Opaque Surface", *Appl. Opt.*, **4**, 767-773, 1965.

Optical Instrumentation for Coatings Characterization

SOC-600 Hand-Held Directional Reflectometer (HHDR)

Measures BRDF of A Sample at Over 30,000 Reflectance Angles
- Varying Incidence Angle from 0° to 85°
- Currently 3-5 μm and 8-12 μm Bands
- Visible/Spectral IR Heads in Development
- Computes HDR from BRDF
- Displays Real Time Images of BRDF
- Providing a Pass/Fail Indication for HDR & BRDF
- Frame Rates Up To 60 Per-Second

SOC-400 Surface Measurement System

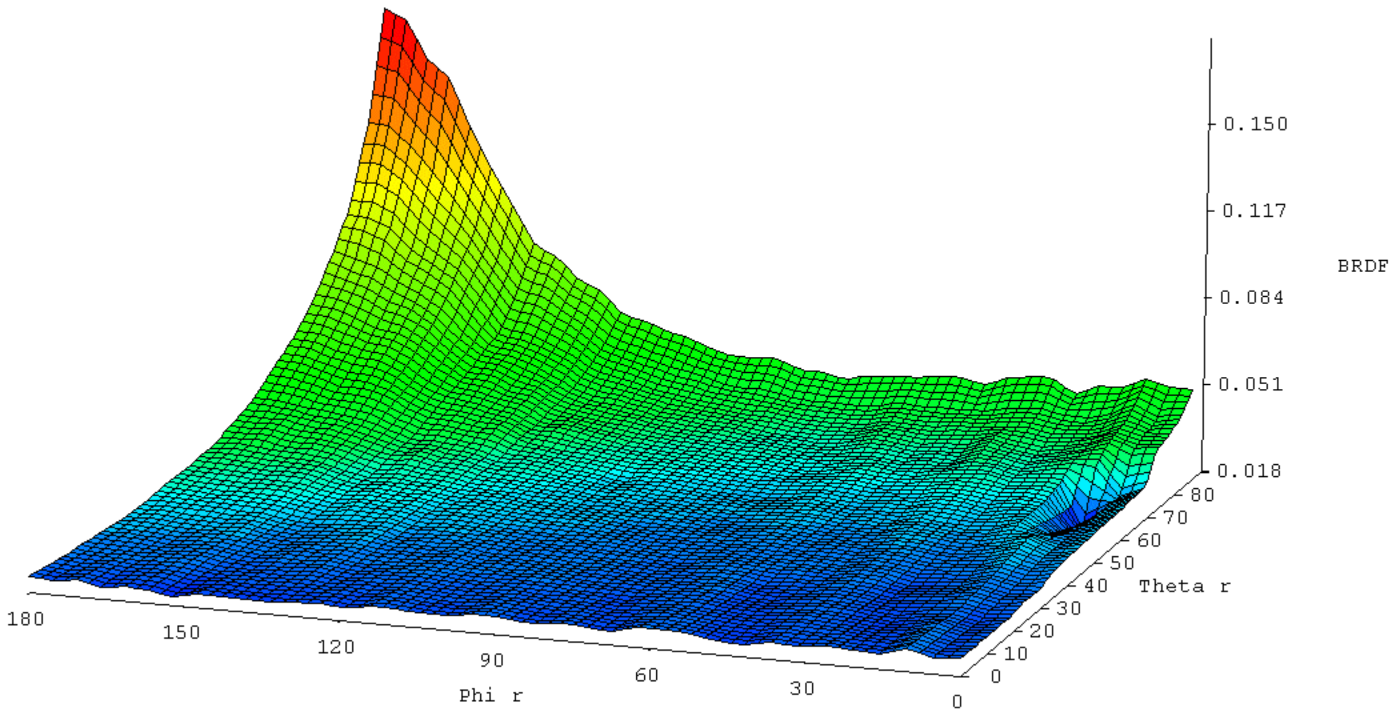


Handheld FTIR for Lab/Field Spectroscopic Analysis
- Optical Heads for Specular, Diffuse and Hemispheric Measurements
- Spectral Coverage from 2-25 μm, 2,4,8,16,32 cm^{-1} Resolution
- Longneck Accessory for Remote Sampling and Visualization
- Accessories for Non-KBr analysis of Powders
- Diffuse Head for Surface Inspection of Contaminants and Films
- Robotic Control for Matrix Mapping of Surfaces

BRDF Measurements

Army Green 383 Camouflage Paint

λ = 0.5 microns θ_i = 50^o



Reflection and Transmission from a Plane Medium

- Fresnel Coefficients for Oblique Incidence

$$r_l = \frac{E_{lr}}{E_{li}} = \frac{\cos\Theta_t - m\cos\Theta_i}{\cos\Theta_t + m\cos\Theta_i} \qquad \text{Parallel} \qquad t_l = \frac{E_{lt}}{E_{li}} = \frac{2\cos\Theta_i}{\cos\Theta_t + m\cos\Theta_i}$$

$$r_r = \frac{E_{rr}}{E_{ri}} = \frac{\cos\Theta_i - m\cos\Theta_t}{\cos\Theta_i + m\cos\Theta_t} \qquad \text{Perpendicular} \qquad t_r = \frac{E_{rt}}{E_{ri}} = \frac{2\cos\Theta_i}{\cos\Theta_i + m\cos\Theta_t}$$

Where: $m\sin\Theta_t = \sin\Theta_i$ (Snell's Law)

$m = (n - ik)$ Complex Refractive Index

Unpolarized Reflection and Transmission:

$$R(\Theta_i) = \tfrac{1}{2}\left(|r_l|^2 + |r_r|^2\right) \quad \text{and} \quad T(\Theta_i) = \tfrac{1}{2}\left(|t_l|^2 + |t_r|^2\right)$$

Absorption in a Medium

- EM Poynting Vector for Complex Refractive Index $m = (n + ik)$

$$S = \tfrac{1}{2}\,\mathrm{Re}\left\{\sqrt{\frac{\varepsilon}{\mu}}\right\}\left|E_o\right|^2 \exp\left(-\tfrac{4\pi k}{\lambda}\right)\hat{e}$$

- Irradiance, *I [energy/area/time]*, is magnitude of *S*
- Energy absorbed in medium over path, *z*, is

$$I = I_o e^{-\alpha z}$$

- The Absorption coefficient is defined as

$$\alpha = \frac{4\pi k}{\lambda}$$

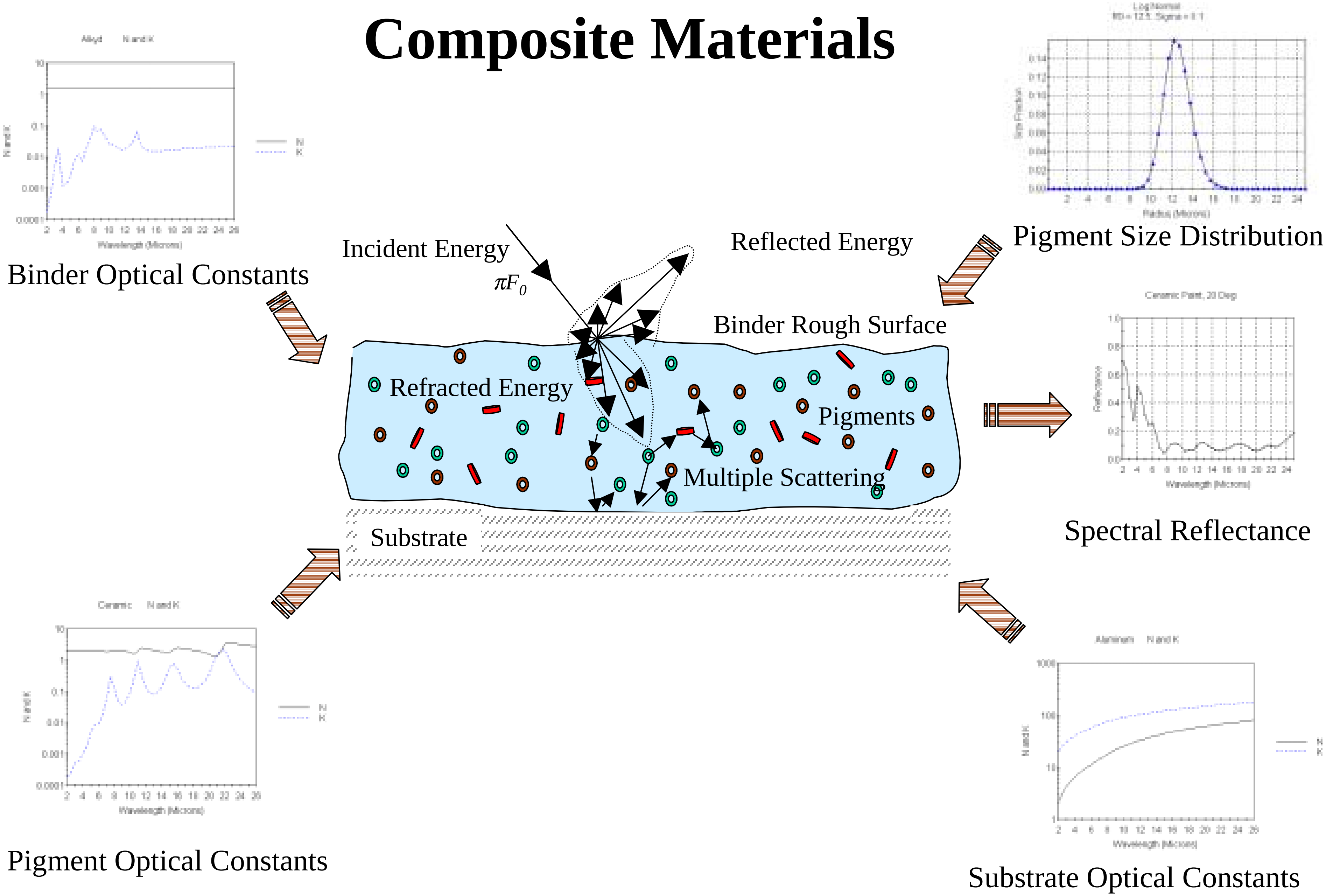
Optical Theory of Materials

- Frequency Inter-Dependence of the Real and Imaginary parts is given by the Kramers-Kronig (Dispersion) Relations

$$\varepsilon'(\omega) = 1 + \tfrac{2}{\pi} \int_0^\infty \frac{\Omega \varepsilon''(\Omega)}{\Omega^2 - \omega^2} \, d\Omega$$

- Phenomenological Models Used to Describe Frequency Dependence
  - Lorentz Model for Damped Electronic, Molecular and Lattice Vibrations
  - Debye Model for Molecular Polarizability
  - Drude Model for Free Electrons in Metals

Optical Phenomenology of Composite Materials



Analytical Techniques

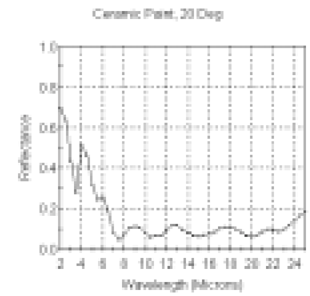
- Mie/Non-Spherical Techniques for Calculating Pigment Single Scattering
- Multiple Scattering Radiative Transfer Used for Volume Scattering
- Rough Surface Scattering Used for Binder Interface
- Radiative Coupling of Surface and Volume Scattering

Scattering Coatings Computer Aided Design (ScatCad) Code

- Implements Single Scattering and Multiple Scattering Radiative Transfer Techniques for Engineering Analysis of Pigmented Coatings
- Predicts the Spectral BRDF and HDR Based on the Optical Constants and Micro-Physical Composition of the Coating
- Windows 95/98/NT PC Based
- Provides Modules for Optical Constant Analysis
- Interfaces to SOC-200/600 BDR and SOC-100/400 HDR Measurement Systems

Analysis Based Coatings Design

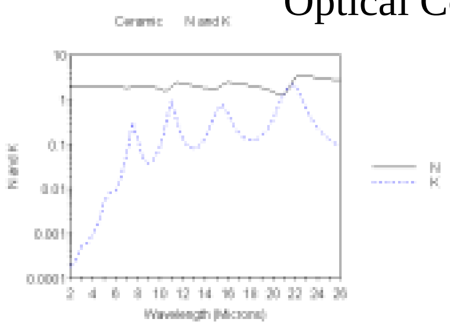
Optical Characterization of Materials

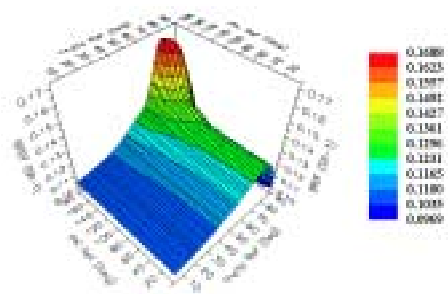


ScatCad Analysis

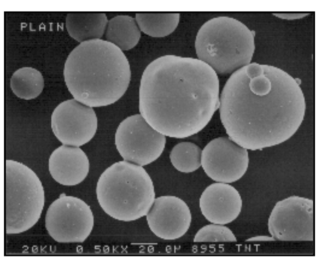
Spectral Directional and Bidirectional Reflectance

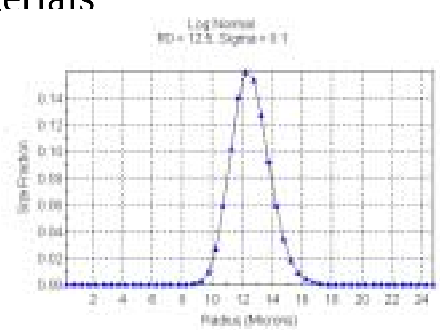
Optical Constants





Physical Characterization of Materials





Pigment Single Scattering

- Mie Theory for Homogeneous and Layered Spherical Pigments
  - 20 Layer Sphere Algorithm Developed by Weisbrod (MDTI-TM-92-01, McDonnell Douglas, 1992)
- Non-Spherical Single Scattering Techniques
  - Henyey-Greenstein, 2 Parameter Phase Function
  - T-Matrix for Axially Symmetric Particles (Mishchenko, *Appl. Opt.*, **32**, 4652-4666, 1993)
  - Discrete Dipole Approximation for Non-Homogeneous/Irregular Particles (Draine and Flatau, *J. Opt. Soc. Am.*, **11**, 1491-1499, 1994)

Radiative Transfer Analysis

Radiative Transfer Equation

$$\mu \frac{dI(\theta,\phi)}{d\tau} = -I(\theta,\phi) + \frac{\omega_0}{4\pi}\int_{4\pi} p(\theta',\phi',\theta,\phi) I(\theta',\phi') d\omega'$$

$$+\frac{\omega_0}{4} p(\theta_0,\phi_0,\theta,\phi) F_o e^{-\tau/\mu_0} + (1-\omega_0) B(T).$$

Where

ω_o is the single scattering albedo

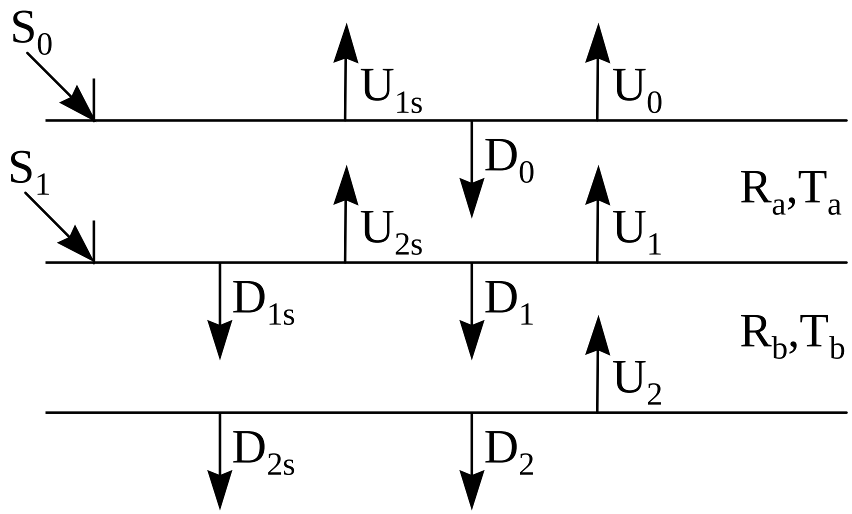
$p(\theta',\phi',\theta,\phi) = p(\cos\alpha)$ is the phase function

F_o is the incident source radiation

B(T) is the thermal emission

$\mu = \cos\theta$

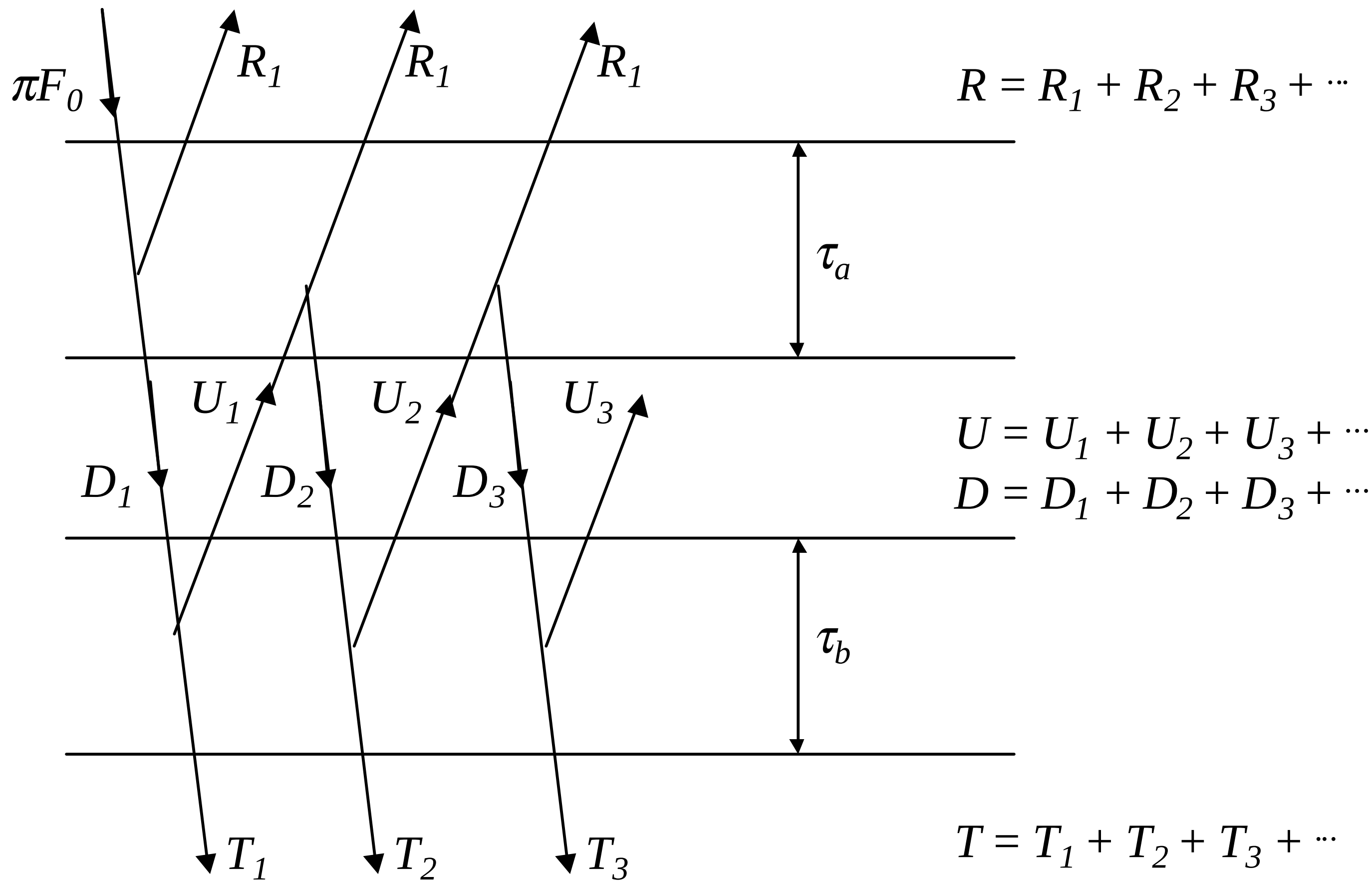
HDR Analysis



- Extension of Kubelka-Munk Two-Flux Analysis
- Uses Three-Flux Approximation to Radiative Transfer Equation
  - Provides Rapid Spectral Calculations for Design Optimization
- Considers Multiple Paint Layers Over Substrate
  - Surface Scattering Not Included
- Binder Absorption Treated as Additional Pigment Absorption

$$\text{mean free path} = l_m = 1/(N\pi r^2) \qquad \Delta C_{abs} = 4\pi\, l_m k_b / \lambda$$

BRDF Analysis - Adding/Doubling



Adding/Doubling Technique

Radiative Adding of Two Layers, τ_a and τ_b

$$S = R_a{*}R_b[1 - R_a{*}R_b]^{-1}$$
$$D = T_a{*}S\, exp(-\tau_a / \mu_o) + S{*}T_a$$
$$U = R_b\, exp(-\tau_a / \mu_o) + R_b{*}D$$
$$R(\tau_a + \tau_b) = R_a + exp(-\tau_a / \mu_o)U + T_a{*}U$$
$$T(\tau_a + \tau_b) = exp(-\tau_b / \mu_o)D + T_b\, exp(-\tau_a / \mu_o) + T_b{*}D$$

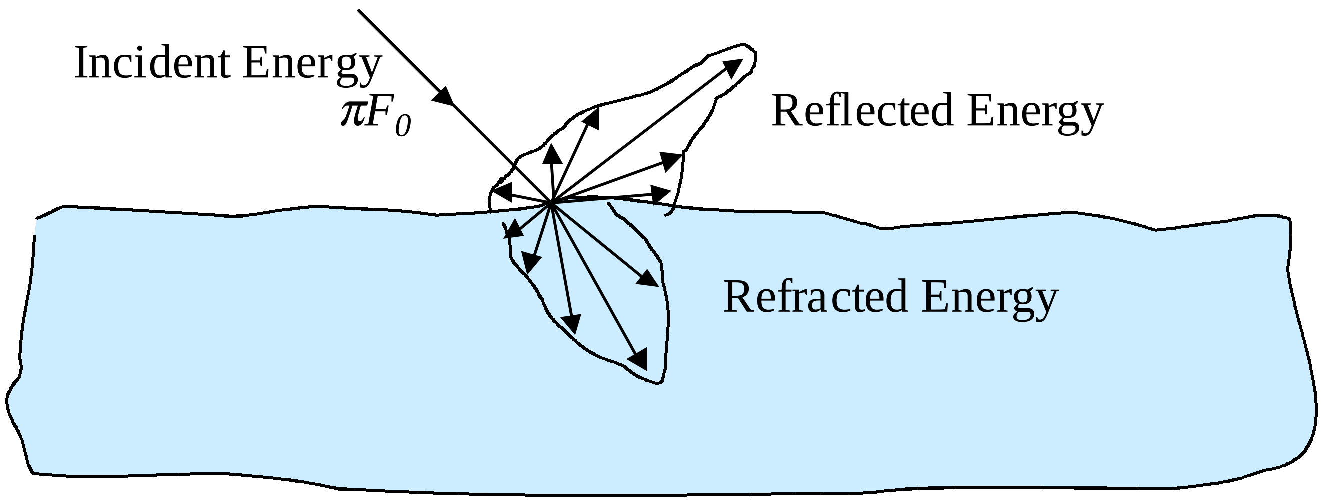
Where $X{*}Y$ terms represent integrals over zenith angle

$$X * Y = \int_0^1 x^m(\mu,\mu')y^m(\mu',\mu_o)2\mu' d\mu'$$

And x^m is the Fourier expansion in azimuth

$$x^m(\mu,\mu_o) = \frac{1}{2\pi}\int_0^{2\pi} x(\mu,\mu_o,\phi)\cos m\phi\, d\phi$$

Rough Surface Scattering



<u>Slightly Rough Surfaces</u>

- •Rice perturbation model
- •Roughness is isotropic
- •Surface slopes are small
- •RMS roughness height < $\lambda/2\pi$

<u>Very Rough Surfaces</u>

- •Tangent-plane approximation
- •Roughness is isotropic
- •Surface curvature << l
- •Correlation length << Sample Length
- •No multiple scattering
- •No shadowing

Surface/Volume Coupling

Modification of Adding/Doubling for Coupling Surface (R_s) and Volume (R_p) Scattering

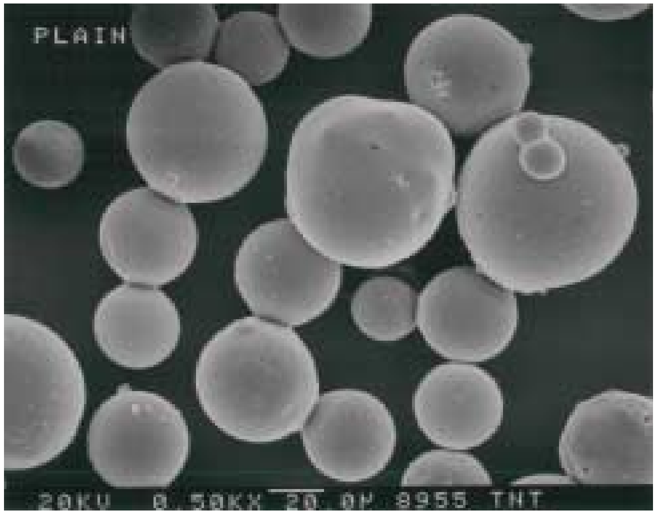
$$S = R_s{*}R_p[1 - R_s{*}R_p]^{-1}$$
$$D = [1 + S]\, T_s$$
$$U = R_p D$$
$$R = R_p + T_s{*}U' n_1^2/n_2^2$$
$$T = T_s{*}D$$

Where

$$X * Y = \int_0^1 \left[x_c(\mu)\frac{\delta(\mu-\mu')}{2\mu} + x^m(\mu,\mu') \right]\left[y_c(\mu')\frac{\delta(\mu'-\mu_o)}{2\mu'} + y^m(\mu',\mu_o) \right] 2\mu' d\mu'$$

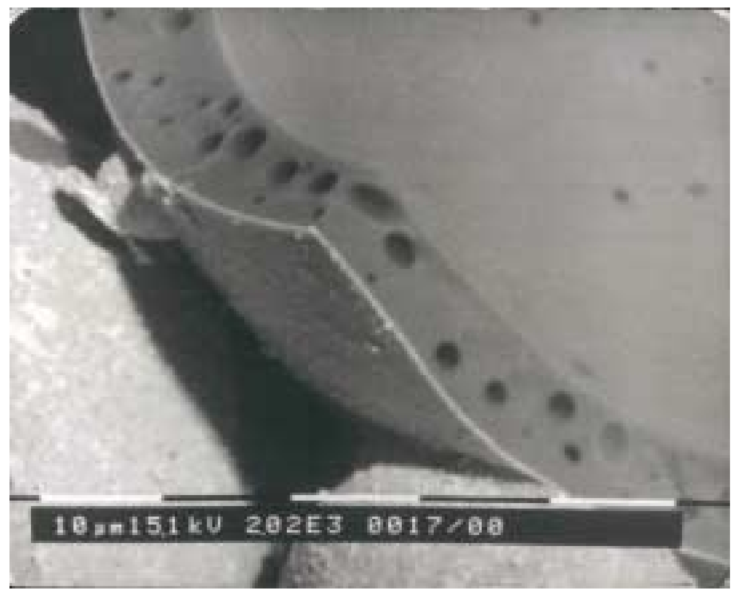
$$= x_c(\mu)y_c(\mu)\frac{\delta(\mu-\mu_o)}{2\mu} + x_c(\mu)y^m(\mu,\mu_o) + y_c(\mu_o)x^m(\mu,\mu_o)$$
$$+ \int_0^1 x^m(\mu,\mu')y^m(\mu',\mu_o)2\mu' d\mu'$$

Model Versus Measurement

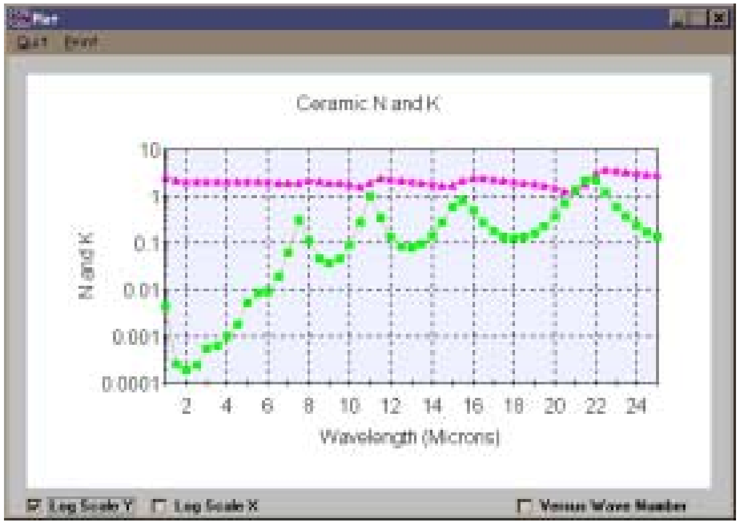


Ceramic (Fly-Ash) Pigment
10 - 70 micron diameter
Log-Normal Size distribution
Mean Diameter 41 microns

Pigment Modeled as Air Core
and 2 Micron Ceramic Layer
Alkyd Binder
Surface Roughness
Commensurate With Pigment
Dimensions

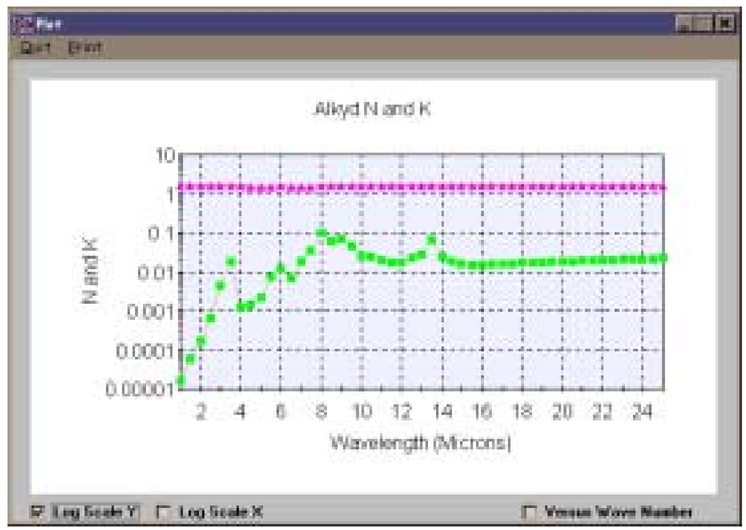


Optical Constant Determination

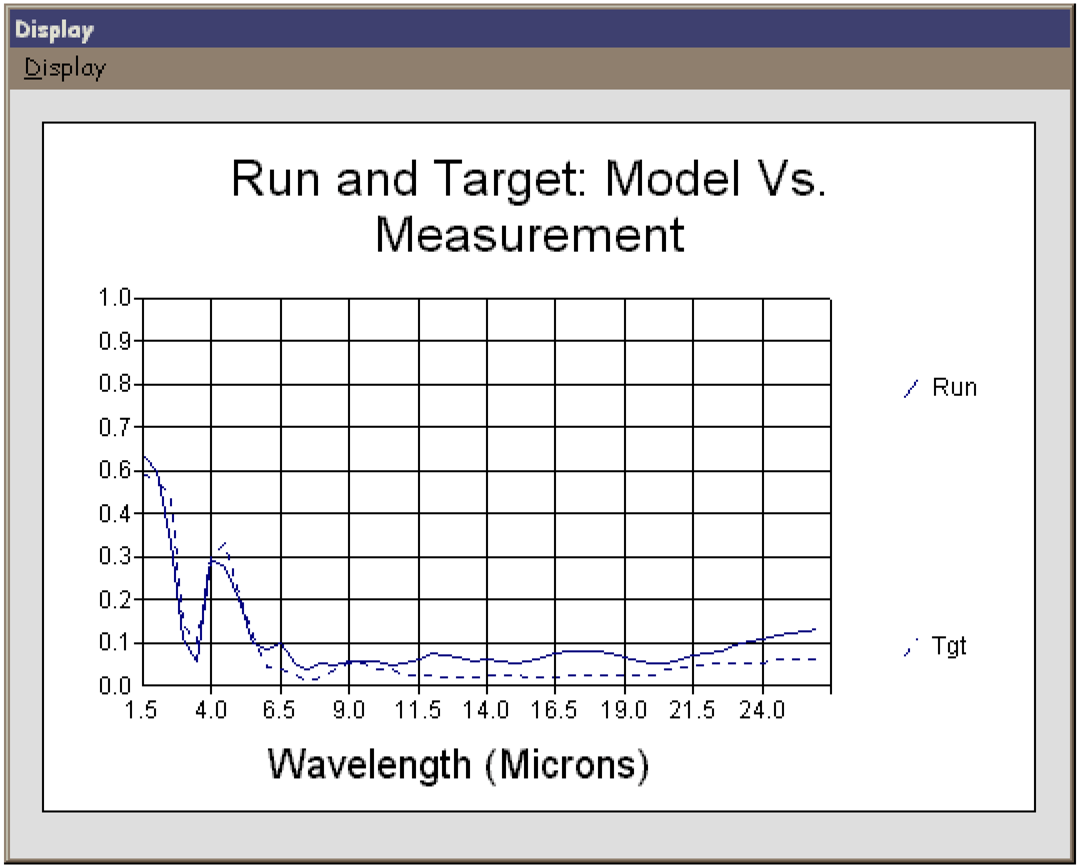


Ceramic Optical Constants Determined From Analysis of HDR Measurement of Micro-Balloon Powder

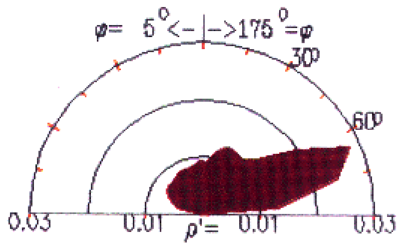
Alkyd Optical Constants Determined From Analysis of HDR Measurement of Thin Film Over Al Substrate

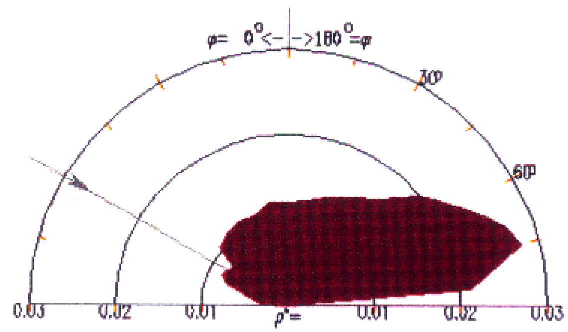


HDR Model Versus Measurements



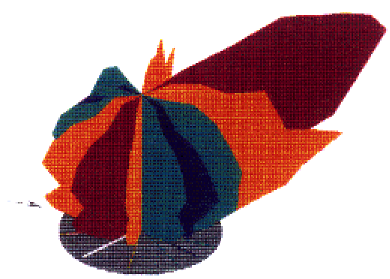
BRDF Model Versus Measurements





ScatCad Calculation

Measurement



Parameterized BRDF Models

- Parameterized BRDF Models used for Signature Simulations
- Specular/Diffuse Partition
  - Implemented in Graphics Accelerator Cards
- Sandford-Robertson Four-Parameter Model
  - Widely Used in Signature Codes (e.g., SPIRITS)
- OPTASM Lorentzian Lobe Model
  - Non-Specular BRDF Lobes, Mueller Matrix

Sandford-Robertson Model

- Based on the Separation of the Spectral and Directional Dependence of the Total BRDF

$$\rho'(\theta_i,\phi_i;\theta_r,\phi_r;\lambda) = f_r(\theta_i,\phi_i;\theta_r,\phi_r)\rho(\lambda)$$

$$f_r(\theta_i,\phi_i;\theta_r,\phi_r) = f_S(\theta_i,\phi_i;\theta_r,\phi_r) + f_D(\theta_i,\phi_i;\theta_r,\phi_r)$$

- Fits Four Parameters to the BRDF

$\rho_D(\lambda)$ = Diffuse Spectral Reflectance

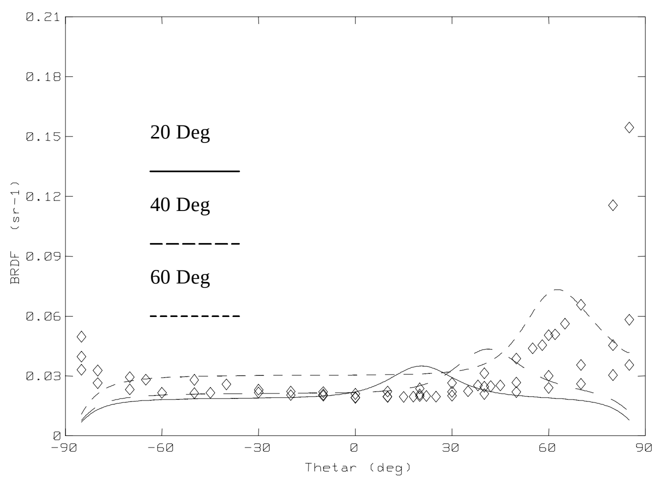
$\varepsilon(\lambda)$ = Spectral Emissivity

b = Grazing Angle Reflectivity

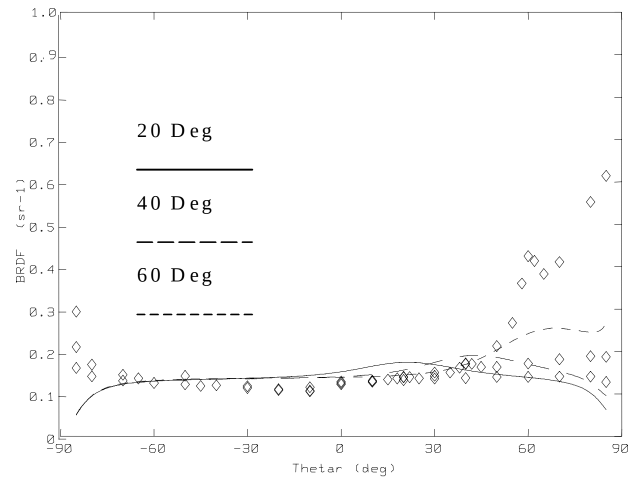
e = Width of Specular Lobe

S-R Model Fit to Green 383

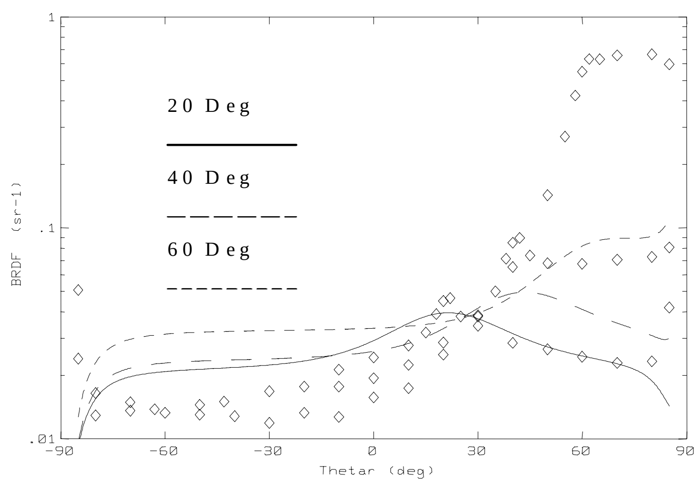
λ = 0.54 microns



λ = 4.4 microns



λ = 10 microns



OPTASM BRDF Model

- Angular Scattering Represented by Lorentzian Shaped Peaks

  ρ_o = Constant Term
  A = Peak Strength
  B = Lobe Width in Degrees
  Γ = Angle Between Peak Direction, $\hat{k}_p$,
  and Viewed Direction, $\hat{k}_r$.

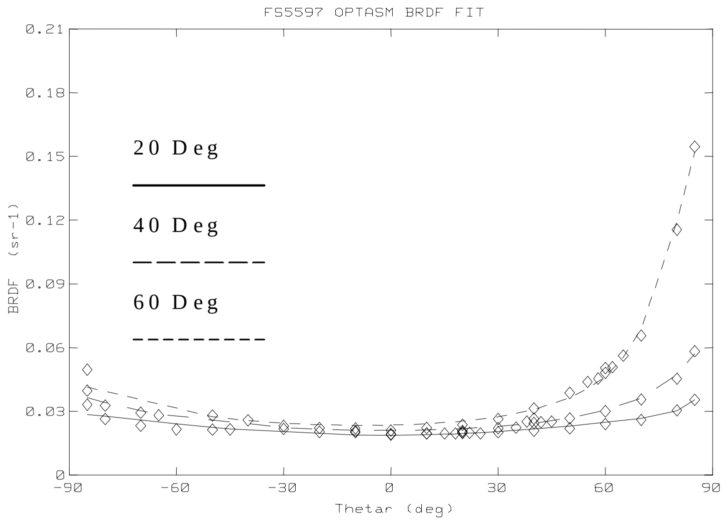
$$\rho'(\hat{k}_i, \hat{k}_r) = \rho_o + A_1 \Big/ \left\{ B_1^2 + 1 - \cos\Gamma_1 \right\} + A_2 \Big/ \left\{ B_2^2 + 1 - \cos\Gamma_2 \right\}$$

$$\Gamma = \cos^{-1}(\hat{k}_p \cdot \hat{k}_r)$$

- 2nd Term Represents Diffuse Scattering, 3rd Term Used for Specular Lobe (Nominally Seven Parameter Model)
- Additional Terms May Be Added for Non-Isotropic and Backscattering Features

OPTASM Model Fit to Green 383

λ = 0.54 microns



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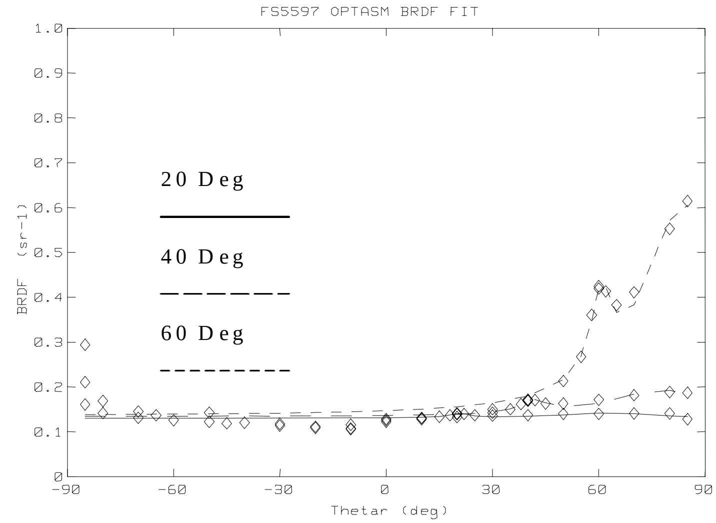

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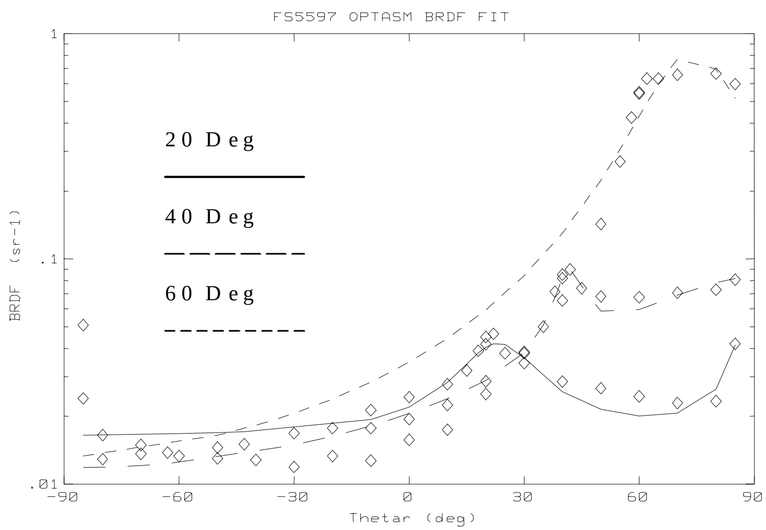
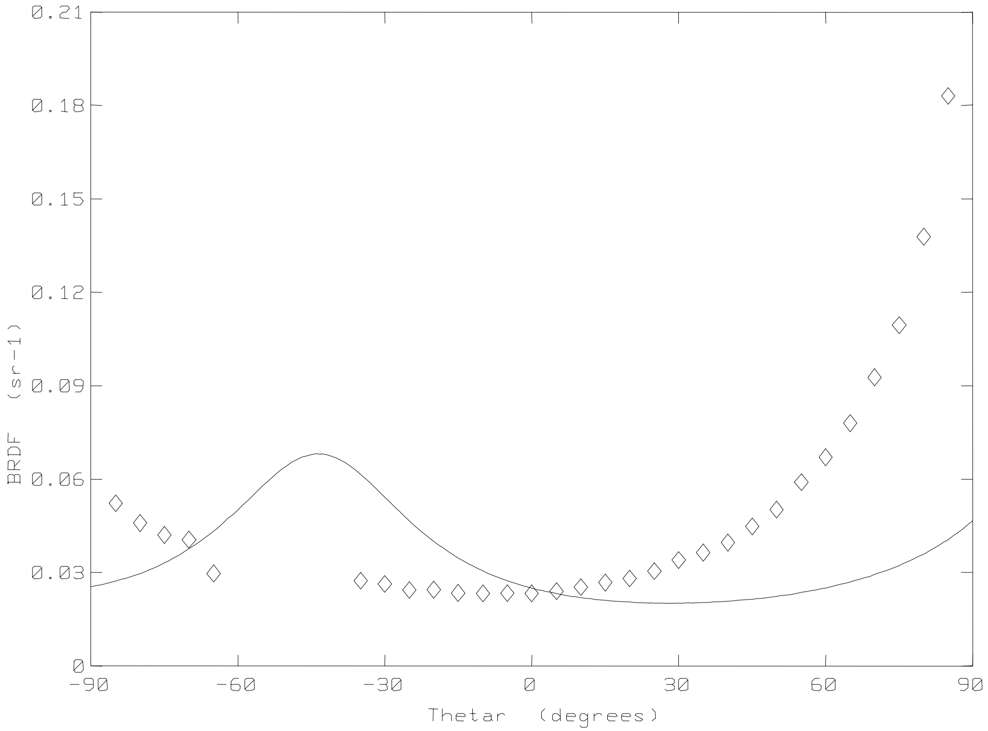


OPTASM BRDF Model Prediction Versus Measurement at 50 Degrees



λ	Fit Param	θ_i		
		20	40	60
0.54	ρ_o	0.224	0.0	0.0
	θ_{p1}	83.2	105.7	185.1
	A_1	4.74e-5	6.81e-3	7.85e-2
	B_1	2.06e-2	5.74e-0	1.3e+1
	θ_{p2}	-2.0	-175.6	88.5
	A_2	-6.6e-1	7.38e-2	1.61e-2
	B_2	-2.4e+2	2.5e+2	8.87e-0
4.44	ρ_o	0.130	0.133	0.132
	θ_{p1}	21.0	41.7	60.7
	A_1	5.50e-4	2.35e-3	6.42e-3
	B_1	2.4e+0	3.48e-0	2.56e-0
	θ_{p2}	62.6	77.3	84.0
	A_2	3.89e-3	1.56e-2	7.67e-2
	B_2	1.1e+1	1.2e+1	9.57e-0
10.0	ρ_o	0.016	0.0	0.0
	θ_{p1}	23.2	41.8	73.8
	A_1	1.02e-2	3.85e-3	1.94e-1
	B_1	8.8e+0	3.30e-0	1.0e+1
	θ_{p2}	92.6	92.3	85.0
	A_2	1.21e-3	7.57e-2	9.94e-5
	B_2	1.3e+0	3.3e+1	1.0e+1

Conclusions

- Complex BRDF Phenomenology is a Significant Feature for Visible/IR Signature Simulations
- Optical Measurements and Phenomenological Models Can Provide Qualitative/Quantitative Insight Into the Optical Properties of Coatings and Surfaces
- ScatCad is a Phenomenological Model for Engineering BRDF and HDR Analysis of Pigmented Coatings
- Use of Parameterized BRDF Models Depends on the Quality of the Fit and the Ability of the Parameters to be Interpolated/Extrapolated to Other Angles